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Waste-to-energy: A way from renewable energy sources to sustainable development

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ABSTRACT

Nowadays, energy is key consideration in discussions of sustainable development. So, sustainable development requires a sustainable supply of clean and affordable renewable energy sources that do not cause negative societal impacts. Energy sources such as solar radiation, the winds, waves and tides are generally considered renewable and, therefore, sustainable over the relatively long term. Wastes and biomass fuels are usually viewed as sustainable energy sources. Wastes are convertible to useful energy forms like hydrogen (biohydrogen), biogas, bioalcohol, etc., through waste-to-energy technologies.

In this article, possible future energy utilization patterns and related environmental impacts, potential solutions to current environmental problems and renewable energy technologies and their relation to sustainable development are discussed with great emphasis on waste-to-energy routes (WTERs).

Contents

1. Introduction

Investigations of alternative energy strategies have recently become important, particularly for future world stability. The most important property of alternative energy source is their environmental compatibility. Inline with this characteristic, renewable energy sources (mainly organic waste materials to energy) likely will become one of the most attractive substitutes in the near future.

Renewable waste materials from agriculture [1–5], industries [6–12] and domestic [13–18] sources are convertible to useful energy forms like biohydrogen, biogas, bioalcohols, etc., through waste-to-energy routes (WTERs) for sustainable growth of the world.

Normally, framework of four energy paths is considered to attain sustainability with existing and alternative routes. These energy paths are: Path (1), continuation of current energy use technologies with amendments; Path (2), universal adoption of advanced energy technologies for transportation and electricity generation; Path (3), the production of alternative renewable energy sources from waste and biomass resources to supplement conventional energy production processes; and Path (4), the development of centralized clean energy production routes and distribution systems.

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The purpose of this study was to review the potential associated with Path 3 for energy resource sustainability within the context of energy resource production routes (microbial conversion routes-fermentation), the adoption of WTER technologies for transportation and electricity generation, and the production of alternative fuels including biogas and hydrogen gas (H_2) and techno-economic growth and limitations for selected WTER.

2. World global problems and renewable energy

Effects of the utilization of fossil fuels, such as global climate change, world energy conflicts and energy source shortages, have increasingly threatened world stability. Their negative effects are observed at all levels of the society, i.e. locally, regionally and globally. These global world problems can be summarized through the following three sections:

- Decrease in fossil fuel reserves due to world population growth and increasing energy demand.
- Global climate change due to the increase of CO_2 concentration in the atmosphere.
- Increase in levels of wastes (solid/liquid) due to increase in population among world.

Various types of wastes from agricultural (plant and animal wastes), industrial (sugar refinery, dairy wastes, confectionary waste, pulp and paper, tanneries and slaughter houses) and residential (kitchen waste and garden waste) sectors are the potential renewable energy sources to attain sustainability and for switchover to waste-to-energy routes (WTERs).

All over the world lots of R&D is going to solve the local, regional and global problems, discussed in above sections. Most of the researchers show their reliance on renewable energy technologies (RET) for sustainable development and long lasting life on this planet earth for their daily energy needs through waste-to-energy routes (WTERs), that do not cause negative societal impacts. Among all the countries of the world, European Union countries showed a remarkable R&D work on this (RET), for example, Meyer et al. were calculated a scenario for sustainable development through renewable energy sources for Denmark, Norway and Sweden separately for 2030 [19]. Similarly, Panoutsou et al. [20] reviewed the future potential of biomass resources (a renewable source) in Europe based on various sectors like agriculture, industrial, etc. This article also highlights the cut in waste generation amount in EU countries, through new waste prevention initiatives, better use of resources and encouraging a shift to more sustainable consumption patterns.

Energy sources such as solar radiation, the winds, waves and tides are generally considered renewable and therefore, sustainable over the relatively long term. Sustainable energy sources that are abundantly available can:

- Reduce or stop conflicts among countries regarding energy reserves.
- Facilitate or necessitate the development of new technologies through WTER.
- Reduce air, water and land pollution and the loss of forests.
- Reduce energy-related illnesses and deaths.

Accordingly, the transition to a sustainable renewable resource should be encouraged, and developing countries, in particular, should increase investments in renewable waste-to-energy routes (WTERs) from various sectors.

3. Potential substitutes of waste-to-energy routes (WTERs)

World requirements for energy will increase by a factor of about six times by 2100. If this demand is bifurcated between developed and developing countries than in the developed countries, there is no shortage of power. Whereas, in the developing countries like India and China, the ratio of energy available to energy required is highly incompatible. This uneven energy distribution in the world, a technology needs to be developed to serve as a secondary source of energy and mitigate energy crisis. It would be wise to develop other fuels, which do not give so much carbon dioxide and can be easily produced with the use of environmental waste. WTER technology may be perceived as a potential alternative as it not only provides renewable source of energy but also utilizes recycling potential of degradable-organic portion of solid waste generated by a numerous activities. Here, only two potential substitutes for WTER technology are considered and reviewed in this article.

3.1. Biogas technology (BT)

In 1776, for the first time, the Italian Physicist, Volta, demonstrated methane in the marsh gas, generated from organic matter in bottom sediments of ponds and stream. Under anaerobic conditions, the organic materials are converted through microbiological reactions in to gases (biogas) and organic fertilizer (manure). Biogas and manure are the end products obtained from BT whereas conventional composting process produces only manure as the product after decomposition of solid organic waste. Thus, comparatively BT could be considered as better option for its compactness, cleaner operation and better product range (i.e. both gas as energy source and processed solid waste as manure). Methane is the main constituent of biogas. About 90% of energy of substrate is retained in methane. It is used mainly for cooking, lighting and in internal combustion engines to power water pumps and electric generators. The most economical benefits are minimizing environmental pollution and meeting the demand of energy for various purposes. In India, the Ministry of New and Renewable Energy (MNRE) (Government of India) has declared a National Master Plan in 1994, which incorporates BT as one of the major waste-to-energy options to be developed and adopted in the country [21].

3.1.1. Efficient feedstocks

A variety of waste sources like urban, agriculture, industrial sectors, vegetable markets, etc., generate huge quantities of solid waste containing a sizeable proportion of biodegradable-organic matter with municipal solid waste (MSW) having largest proportion. This material, if processed anaerobically, will not only generate significant quantity of biogas, i.e. about 250–350 m^3/tonne of waste (NEERI Report, 1996) and manure but will also reduce the load on landfilling and will in turn prevent the degradation of environmental quality due to uncontrolled decomposition of organic matter in the landfills. Bouallagui et al. studied both fruit and vegetable wastes together for biogas production [5,22]. Similar type of studies were done by Ranade et al. [23], Mataalvarez et al. [24] and Pavan et al. [25] taken market waste (rotten vegetables, fruit skins, potatoes, onion, etc.) and household solid waste respectively intensively used for methane production. Demirel and Scherer [26] did the laboratory-scale study was to investigate the long-term anaerobic fermentation of an extremely sour substrate, an energy crop, for continuous production of methane (CH_4) as a source of renewable energy. The sugar beet silage was used as the mono-substrate, which had a low pH of around 3.3–3.4, without the addition of manure. The mesophilic biogas digester was operated in a hydraulic retention

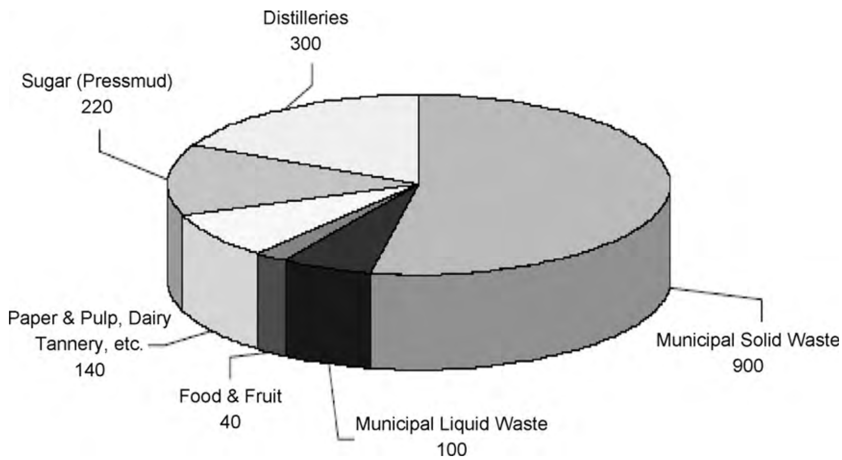

Fig. 1. Energy recovery potential (MWe) of different wastes from urban and industrial sectors.

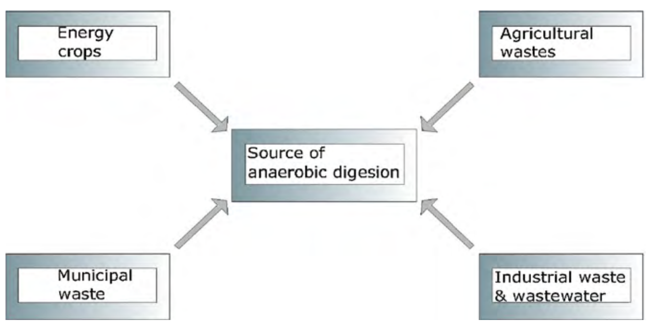

Fig. 2. Different sources of waste feedstocks for biogas energy.

time (HRT) range between 15 and 9.5 days, and an organic loading rate (OLR) range of between 6.33 and 10 g $VS^{-1}\,l^{-1}\,d^{-1}$. Energy recovery potential of different organic wastes from urban and industrial sector in form of Biogas has been depicted in Fig. 1 [27].

Fig. 2 illustrates the various successful feedstocks for biogas energy and the process (Fig. 3) used is anaerobic digestion (AD) to degrade the waste feedstock materials.

Anaerobic digestion process takes place in a warmed, sealed airless container (the digester), which creates the ideal conditions for the bacteria to ferment the organic material in oxygen-free conditions. The digestion tank needs to be warmed and mixed thoroughly to create the ideal conditions for the bacteria to convert organic matter into biogas (a mixture of carbon dioxide, methane and small amounts of other gases). The proper design and scale-up of anaerobic reactors requires knowledge regarding correlations between reactor configuration and process efficiency to set the limits for the biochemical operating parameters. Anaerobic digestion process takes place mainly by two types, i.e. mesophilic digestion (temperature range = 30–35 °C and retention time for 15–30 days) and thermophilic digestion (temperature range = 55 °C and retention time for 12–14 days). The production of biogas through anaerobic digestion offers significant advantages over other forms of waste treatment, including:

- Less biomass sludge is produced in comparison to aerobic treatment technologies.
- Successful in treating wet wastes of less than 40% dry matter [28].
- More effective pathogen removal [29–31]. This is especially true for multi-stage digesters [32] or if a pasteurization step is included in the process.
- Minimal odour emissions as 99% of volatile compounds are oxidatively decomposed upon combustion, e.g. H_2S forms SO_2 [33].
- High degree of compliance with many national waste strategies implemented to reduce the amount of biodegradable waste entering landfill.
- The slurry produced (digestate) is an improved fertilizer in terms of both its availability to plants [34].
- A source of carbon neutral energy is produced in the form of biogas.

Various types biogas digesters like complete mix, plug flow, covered lagoon and fixed film digesters are discussed in the

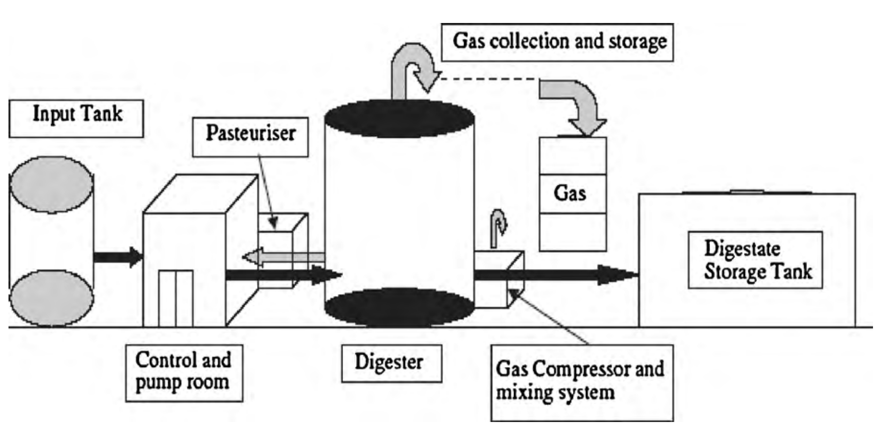

Fig. 3. Schematic layout for an Anaerobic Digester system.

Table 1
Some waste biomass feedstock used for hydrogen production.

Biomass feedstock	Major conversion technology
Almond shell	Steam gasification
Pine sawdust	Steam reforming
Crumb rubber	Supercritical conversion
Rice straw/Danish wheat water	Pyrolysis
Microalgae	Gasification
Tea waste	Pyrolysis
Peanut shell	Pyrolysis
Maple sawdust slurry	Supercritical conversion
Starch biomass slurry	Supercritical conversion
Composed municipal refuse	Supercritical conversion
Kraft lignin	Stem gasification
MSW	Supercritical conversion
Paper and pulp waste	Microbial conversion

literature [35] and basically stirred tank type reactors, which is ideally suited to high moisture content wastes.

Hence, the production of biogas through waste-to-energy route technologies and sources is gaining importance for supplementing the fuel/energy requirements.

3.2. Hydrogen energy

As a sustainable energy supply with minimal or zero use of hydrocarbons, hydrogen is a promising alternative to fossil fuels. It is a clean and environmentally friendly fuel that produces water instead of greenhouse gases when combusted. It seems to be logical conclusion for numerous environmental problems like acid rain and greenhouse effect.

3.2.1. Efficient feedstocks

There are many feedstocks and techniques available to harness hydrogen from fossil fuel, water and biomass. Among these electrolysis of water, steam reforming of hydrocarbons and auto-thermal processes are well-known methods for hydrogen gas production, but not cost-effective due to high energy requirements. But, carbohydrates rich, nitrogen deficient solid wastes such as cellulose [16,36–39] and starch [40–50] containing agricultural and food industry wastes and some food industry wastewaters such as cheese whey [51], olive mill and bakers yeast [51] industry wastewaters can be used for hydrogen production by using suitable bioprocess technologies or other WTERs. This bioprocess for hydrogen production referred as biological hydrogen. Pure and mixed cultures [52,53] known to produce hydrogen from carbohydrates include species of Enterobacter [54,55], Bacillus [56] and Clostridium [57–59] in different reactor configurations like continuous, membrane bioreactor and UASB reactor has been reported in the literature [45–49].

For sustainable hydrogen production through WTERs the feedstock will need to meet certain criteria. These are that the feedstock will be principally organic carbon source, be produced from sustainable (waste) resources, be of sufficient concentration

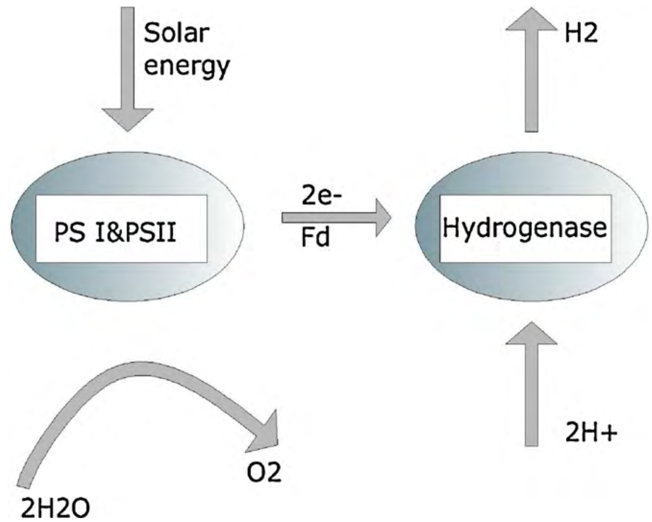

Fig. 4. Schematics of direct biophotolysis.

that fermentative conversion and energy recovery is energetically favorable, require minimum pre-treatment and be of low cost.

Utilization of aforementioned wastes for hydrogen production provides inexpensive energy generation with simultaneous waste treatment. Some biomass feedstock (agricultural and forest product residues of hard wood, soft wood and herbaceous species) also used for hydrogen production mentioned in the literature (Table 1).

Generally, conventional gasification of biomass and wastes employed with goal of maximizing hydrogen production in the temperature range of 600–1000 °C. The reaction is as follows:

$$\text{Biomass} + O_2 \rightarrow CO + H_2 + CO_2 + \text{Energy}$$

A comparison of different process routes for hydrogen production on the basis of their relative merits and demerits is given in Table 2.

For global environmental considerations, production of hydrogen by biological reactions from renewable organic waste sources represents an important area of bio-energy production. Biological hydrogen production can be classified into four different groups: (i) direct biophotolysis, (ii) indirect biophotolysis, (iii) photo-fermentation and (iv) dark fermentation. All these processes are controlled by the hydrogen producing enzymes, such as hydrogenase and nitrogenase and their role in different processes depicted by Figs. 4–7 [60]. Among all these microbial conversion process, dark fermentation route is more feasible technology with commercial values and offer an excellent potential for practical application and integration with emerging hydrogen and fuel cell technologies [61]. Biological hydrogen production has several advantages also when compared to photo-electrochemical or thermo-chemical processes, due to low energy requirement and investment cost.

Table 2
Merits and demerits of different processes of waste biomass conversion to hydrogen.

Process	Merits	Demerits
Thermo-chemical gasification	Maximum conversion can be achieved	Significant gas conditioning is required; removal of tars is important
Fast pyrolysis	Produces bio-oil which is the basis of several processes for development of fuels, chemicals	Chances of catalyst deactivation
Solar gasification	Good hydrogen yield	Requires effective collector plates
Supercritical conversion	Can process sewage sludge, which is difficult to gasify	Selection of supercritical medium
Microbial conversion	Waste (solid/liquid) can be treated simultaneously and generation of some secondary metabolites	Selection of suitable microbes

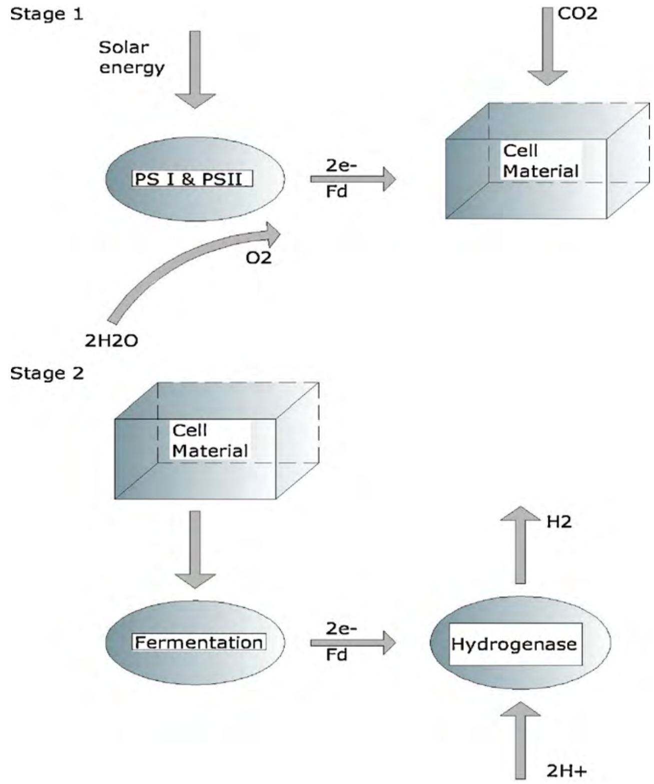

Fig. 5. Indirect biophotolysis for hydrogen production.

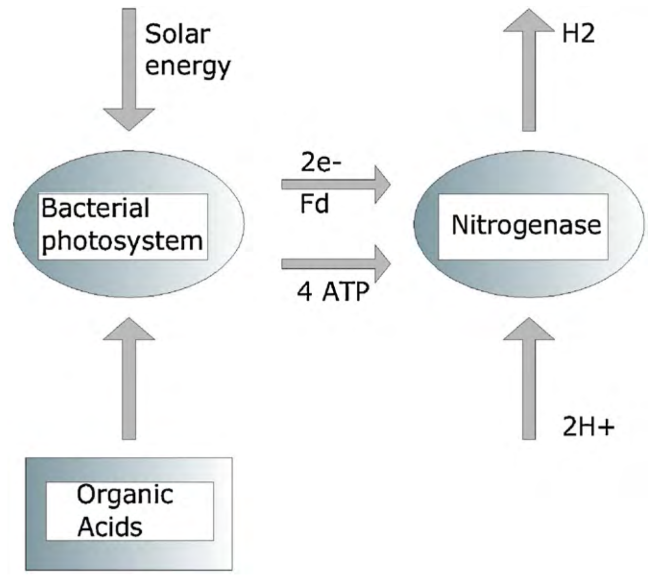

Fig. 6. Photo-fermentation schematics.

Hydrogen has a heating value of 61,000 Btu/lb, while methane has a heating value of 23,879 Btu/lb, nearly one third that of hydrogen. Similarly, comparison of hydrogen and other fuels in respect to key properties is given in Table 3.

Fig. 8 shows the supporting and opposing factors for the development of hydrogen economy. It has been predicted that H_2 will be the main source of energy by the year 2100 [62]. Thus, hydrogen from renewable sources might be considered as the ultimate clean and climate neutral energy system.

4. Techno-economic aspects of WTER production technologies

Many techno-economic assessments of WTE from renewable residues find place in the literature. However, there sources also contain discussions, insights and recommendations on WTE feasibility and research as well as an assessment of WTE

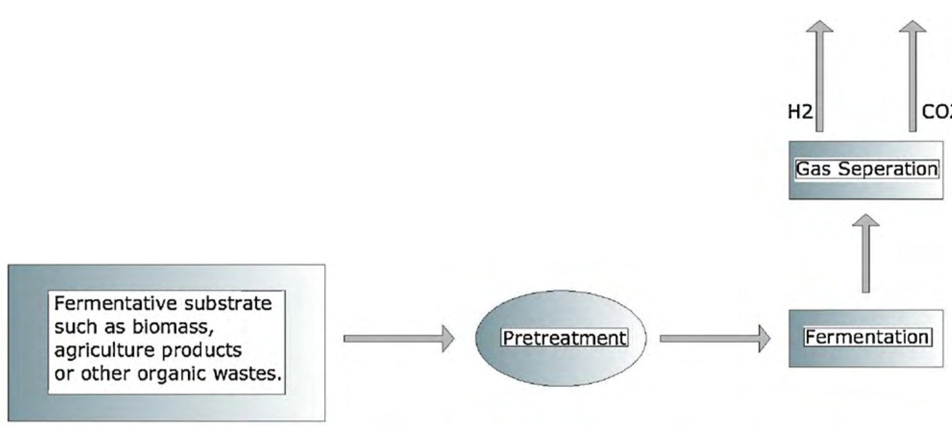

Fig. 7. Hydrogen production by dark fermentation.

Table 3
Comparison of key properties for hydrogen and other fuels.

Fuel type	Energy per unit mass (J/kg)	Energy per unit volume (J/m^3)	Specific carbon emission (kg C/kg fuel)
Liquid hydrogen	141.90	10.10	0.00
Gaseous hydrogen	141.90	0.013	0.00
Fuel oil	45.50	38.65	0.84
Gasoline	47.40	34.85	0.86
Methanol	22.30	18.10	0.50
Ethanol	29.90	23.60	0.50
Bio diesel	37.00	33.00	0.50
Natural gas	50.00	0.04	0.46

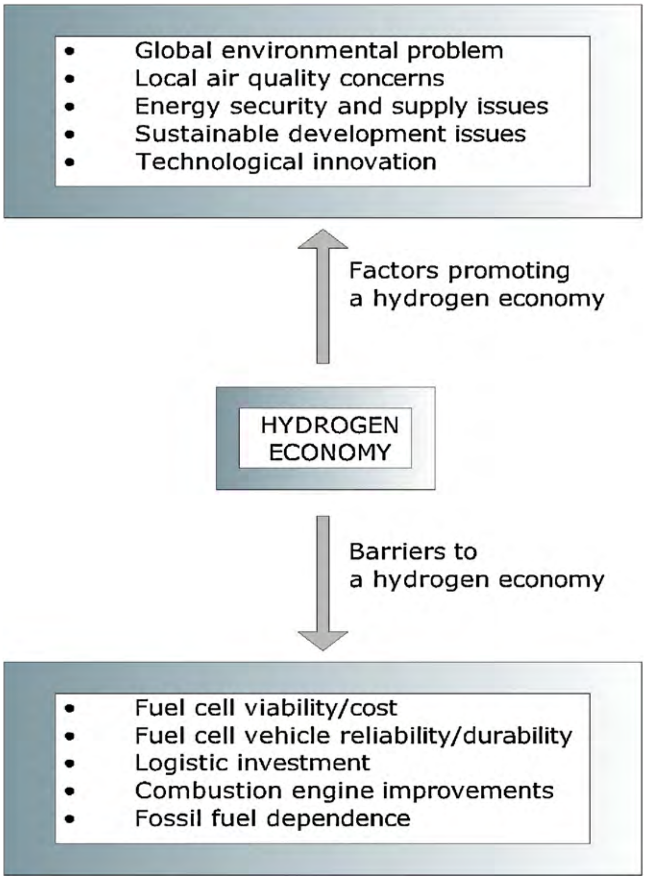

Fig. 8. Factors supporting and opposing the developments of hydrogen economy.

technologies concludes that waste utilization is the most economical process for renewable energy production (biogas and hydrogen/biohydrogen) and to clean the environment.

The review of this study has revealed that biogas and hydrogen could be produced economically from renewable waste feedstock/substrates. An added advantage of waste and biomass as a renewable feedstock is that these are not intermittent, but can be used to produce hydrogen and biogas as and when required. Significant amounts of renewable 'waste' are produced from the agricultural, domestic and industrial sectors across world. This unused resource could be a potential source if efficient and economically viable technologies were available to exploit it.

5. Limitations for WTER technologies

There are, however, several limitations to the development of waste substrates as an immediate energy resource. Foremost is the fact that current anaerobic digestion technologies are not sufficiently efficient to recover usable energy at a cost that is currently competitive with fossil fuel technologies. If we are to utilize renewable waste as a bio-energy resource, substantial improvements in the efficiency of energy recovery will have to be made, or additional value-added benefits related to waste diversion or GHG mitigation will have to developed to make these processes more economically viable. Another key factor in the development of renewable waste substrates as energy resources is the distributed or dispersed nature. Large sources of waste substrates are often located at a distance from potential energy production sites. For example, a significant amount of livestock manure (i.e. cow dung), as much as 25–35% of the total residues, may remain un-recoverable. The collection, transport, and processing of renewable waste also pose a significant challenge to their use in energy production. The costs of these feedstocks are directly proportional to the costs of collection and transportation to energy production sites. With fossil energy sources eventually dwindling and becoming increasingly more expensive, waste-to-energy routes are likely to have future attraction. The improvements in fermentation system yields obtained from better preprocessing and recovery techniques would also help improve their viability in general. Additionally, valuing the collateral avoidance of renewable waste residue-related environmental problems, such as municipal waste landfill, GHG emissions, as achieved through utilizing MSW, can also influence sustainability of WTE approaches.

With these various points in mind, which renewable waste substrate can currently cover the greatest practical potential for energy production in world? While it is clear that additional research is required to improve the efficiency of energy production by anaerobic fermentation processes, certain waste residues offer the potential for significant energy using existing technologies. Industrial waste rich in organic contents are produced in large amounts in urban areas with high energy needs, and thus, could provide usable energy on a sustainable basis to some communities. Large livestock feedstock from agriculture sector close to urban and rural centers also offer a potential for co-digestion of manure with organic municipal solid waste (OMSW) from domestic sector, producing usable energy and value-added fertilizer, as well as reducing their environmental problems.

Energy required for the substrate pre-treatment, purification of the biogas and hydrogen, reactor maintenance, manpower, etc., also limited the WTER technologies. Although low-yield and the rates of energy production may be overcome by selecting and using more effective organisms or mixed cultures, developing more efficient processing schemes, optimizing the environmental conditions, improving the light utilization efficiency and developing more efficient reactors in WTERs.

The significant potential of biogas and hydrogen energy yields shown here through utilizing microbial technologies for existing and otherwise unused renewable waste resources supports the establishment of a focus on this area, including additional research and development on conversion technologies and the creation of commercial incentives to encourage the industrial development of this potential.

Hence, with scientific and engineering advancements, limitations for WTER technologies can be solved and viewed as a key and economically viable component to a renewable based economy.

6. Conclusion

This review finds that WTER products in place of fossil fuels have an excellent potential for high energy content, such as by anaerobic digestion and biological hydrogen production. WTER offers the potential for a distributed energy supply network model, which would be based on on-site biogas and biohydrogen production. Considerable research and development studies are needed to improve the "state of art" in WTER for sustainable development of society and commercialization.

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